Appendix C
Slope Protection

C-l. General

a. Upstream slopes. Upstream slopes require more extensive treatment than downstream slopes because they are exposed to wave action. The required upstream slope protection depends on the expected wind velocities and duration, the size and configuration of the reservoir, the permanent water-surface elevation, and the frequency of the pool elevation. Where a permanent pool exists, elaborate protection below the minimum water surface is seldom needed since erosive action would be negligible below that level, and a selected gravel will afford sufficient protection. Above the permanent pool elevation, protection against wave action is required. On the downstream slope, only erosion from rainfall and surface runoff and/or wind erosion must be considered except for sections that may be affected by wave action in the tailwater pool. A performance survey was made in 1946 covering slope protection for a number of major earth dams (largely Corps of Engineers) in the United States (the results are reported in U.S. Army Engineer Waterways Experiment Station 1949).

b. Probability evaluation. An evaluation of the probability for erosion damage should be made for each slope protection design. The evaluation should consider the effects of each type of erosion: wave, rainfall and surface runoff, and wind erosion. The influence of seepage, freezing and thawing, and ice buildup should be considered, as appropriate. Due to the high cost of slope protection, this evaluation should be accomplished during the survey studies to establish a reliable cost estimate. The final design should be presented in the appropriate feature design memoranda.

c. Bedding layers. Bedding layers beneath riprap should be designed to provide for retention of bedding particles for the overlying riprap and for retention of the material underlying the bedding layer. To satisfy these requirements, multiple bedding layers may be required. The minimum bedding layer thickness should be 9 in. Geotextiles (filter fabrics) should not be used beneath riprap on embankment dams.

C-2. Design Considerations

Slope protection should be provided for the range of frequent and extended reservoir elevations. The slope of the flood hydrograph determines the length of time the pool resides at each elevation. If the response time between the storm and the resulting flood pool is relatively short, the high winds associated with the storm may not have subsided and must be considered in the selection of the design wind. The steepness of the embankment slope, ease of access for maintenance, nature of the embankment materials to be protected, and availability of materials for use as slope protection should be considered in the design. Slopes flatter than 1 vertical on 15 horizontal seldom require slope protection. Embankment slopes of 1 vertical on 6 horizontal and flatter can be traversed easily by construction and maintenance equipment.

a. Classification of embankment slopes for probability of damage. The possibility of damage to the slope varies with the steepness of the slope, nature of the embankment materials, wind speed, fetch, and exposure time to the wave attach. Guidelines for slope classification based on this exposure concept are as follows:

(l) Upstream slope.

(a) Class I: The zone of an embankment slope with maximum exposure to pool elevations during normal project operation. Generally, the Class 1 zone will extend from an upper pool elevation determined by an annual chance of exceedence of 10 percent plus the appropriate wave runup down to a drawdown pool elevation determined by 10 percent chance of occurrence. The embankment elevations in the multipurpose operating range have a near constant exposure and should be Class I.

(b) Class II: The zone of an embankment slope with infrequent exposure to pools. Generally, this is the zone immediately above or below the Class I zone, and damage to the slopes in this zone is usually a result of rainfall and surface runoff, floods during construction, wave attack during the initial reservoir filling, or erosion due to currents. For embankment dams with gated outlet works, the zone and below the top of spillway gates plus wave runup or uncontrolled spillway crest plus wave runup, should be Class II. For embankment dams with ungated outlet works, the zone and below the lower of elevation of the uncontrolled spillway crest plus wave runup or elevation obtained by rounding on the top of multipurpose pool the standard project flood and adding wave runup, should be Class II.

(c) Class III: The zone of an embankment slope with rare exposure to pools. The occurrence of pools above the Class II embankment zone is very infrequent and the duration of these pools is usually short. However, the potential for wave erosion to result in a safety hazard increases as the width of embankment narrows. All embankment slopes above the Class II elevations should be Class III, except at the top of embankment where the safety of the dam during a spillway design flood becomes a primary concern, and a lower class category may be appropriate. Special design considerations for the embankment crest are discussed in paragraph C-2*d*.

(2) Downstream slopes. The embankment slope below the maximum tailwater elevation for the spillway design flood will usually be classified as Class II. In many projects the geographic relationship between the embankment and spillway preclude the necessity for extensive tailwater protection. For projects where large spillway flows discharge near the embankment toe, a hydraulic model test is required to establish the flow velocities and wave heights for which slope protection should be designed.

b. Riprap. Dumped riprap is the preferred type of upstream slope protection. While the term “dumped riprap” is traditionally used, it is not completely descriptive since some reworking of dumped rocks is generally necessary to obtain good distribution of rock sizes. For riprap up to 24 in. thick, the rock should be well graded from spalls to the maximum size required. For thicker riprap protection, a grizzly should be used to eliminate rock fragments lighter than 50 lb. Riprap sizes and thicknesses are determined based on the significant wave height (design wave). The design wave and wave runup will change for different pool levels as a result of variations in the effective fetch distance and applied wind velocity. Riprap in the upstream slope should have a minimum thickness of 12 in. The selection of design water level and wave height should follow the procedures outlined in EM 1110-2-1414. Actual wind, wave, fetch, and stone size will be computed in accordance with algorithms and/or figures in EM 1110-2-1414, “Automated Coastal Engineering System” (Leenknecht, Szuwalski, and Sherlock 1992), and the “Shore Protection Manual” (U.S. Army Corps of Engineers 1984).

(l) Design wind. Use of the actual wind record from the site is the preferred method for establishing the wind speed-duration curve (see paragraph 5-7 of EM 1110-2-1414). For riprap in Class I zone, select the 1 percent wind. For riprap in Class II zone, select a wind between the 10 percent chance and 2 percent chance based on a risk analysis. For riprap in Class III zone, select a wind between 50 percent chance and 10 percent chance based on a risk analysis.

(2) Effective fetch. Compute the effective fetch, in miles, using the procedure explained in paragraph 5-7 of EM 1110-2-1414. Using the Automated Coastal Engineering System (ACES) software (see Leenknecht, Szuwalski, and Sherlock 1992), especially the desktop computer routine for wind wave hindcasting in restricted fetches, will simplify and standardize the computations in conjunction with the methodology described in EM 1110-2-1414. As an alternative, the restricted fetch computations from the “Shore Protection Manual” (U.S. Army Corps of Engineers 1984) can also be used. For design of riprap in a Class I zone, compute the effective fetch for a pool elevation with a 10 percent chance of exceedence. For design of riprap in the Class II zone, compute the effective fetch for the applicable pool elevation (i.e., top of gates, uncontrolled spillway crest, etc.). If another pool level is used to define the elevation Class I or Class II zones, compute the effective fetch for the higher of the two elevations. Riprap will seldom be required for slopes in the Class III zone, but when riprap is selected for a band along the embankment crest, compute the effective fetch for the maximum surcharge pool.

(3) Design wave. Computation of the design wave is explained in EM 1110-2-1414 and “Automated Coastal Engineering System.” By using the algorithm in ACES (see Leenknecht, Szuwalski, and Sherlock 1992) for wind-speed adjustment and wave height design, restricted fetch option, the wave height, and period are computed at the same time the effective fetch is determined. For design of riprap, use the significant wave height (average of the one-third highest waves in a given group). If a vertical wall is part of the design, use a higher wave, i.e., average 1 percent or 10 percent, depending on structure rigidity.

(4) Riprap design. Determine the size of the riprap and the layer thickness using the rubble-mound revetment design in ACES (see Leenknecht, Szuwalski, and Sherlock 1992). This algorithm will give the stone size, layer thickness, and compute wave runup on a riprap slope with an impervious foundation. Use this computed runup in paragraph C-2*b*(2) to check the embankment height.

c. Bedding layers. The gradation of the bedding material should provide for the retention of bedding particles by the overlying riprap layer and for the retention of the material underlying the bedding layer. If the underlying material has low plasticity, the gradation of the bedding material should conform with the following filter criteria.

$$D_{15B} > 5D_{15E} \quad \text{(C-1)}$$

$$D_{15B} < 5D_{85E} \quad \text{(C-2)}$$

$$D_{85B} > D_{15R}/5 \quad \text{(C-3)}$$

D_{15B} = the 15 percent passing the size of the bedding

D_{85B} = the 85 percent passing the size of the bedding

D_{15E} = the 15 percent passing the size of the material to be protected

D_{85E} = the 85 percent passing the size of the material to be protected

D_{15R} = the 15 percent passing the size of the riprap

An intermediate filter layer may be required between the bedding and riprap to prevent washout of the bedding. Bedding layers over erosion-resistant clay materials need not be designed to meet the criteria of Equation C-1 or Equation C-2 but must still satisfy Equation C-3. Each design should produce a specification that defines material sources, gradations, and layer thickness to economically provide the riprap and bedding layers required to protect the embankment.

d. Embankment crest. The top of dam elevation is usually selected much earlier in the design process than is the slope protection. When the slope protection design has been selected, the top of dam elevation should be reviewed to ensure that runup computations (from paragraph C-2*b*(4)) are consistent with the type of protection to be provided. The slope protection near the top of the dam must ensure embankment safety and security to downstream areas. Each embankment dam should be reviewed to determine the needed crest elevations of the upstream slope. Intermittent overtopping by wave runup may be acceptable where access to the top of the dam is not necessary during occurrence of the maximum surcharge pool and when the crest and downstream slope consist of material that will not experience damaging erosion. The slope protection provided at the near crest elevations of the upstream slope may vary for different reaches but must be stable for the design wave used to establish the top of dam elevation.

e. Downstream slope protection.

(l) Where an adequate growth of grass can be maintained, vegetative cover is usually the most desirable type of downstream slope protection. A slope of approximately 1 vertical on 3 horizontal is about the steepest on which mowing and fertilizing equipment can operate efficiently. In arid or semiarid regions where adequate turf protection cannot be maintained, outer embankment zones composed of soils susceptible to erosion (silts and sands) may be protected with gravel or rock spall blankets at least 12 in. thick, have berms with collector ditches provided, and have collector ditches at the embankment toe.

(2) Where the downstream slope is exposed to tailwater, criteria used to establish the required upstream protection should be used for that portion of the slope exposed to wave action. Alternatively, a rock toe may be provided, extending above the maximum tailwater elevation.

f. Alternative slope protection. Alternative slope protection designs that are functional and cost effective may be used. Factors that influence the selection of slope protection are embankment damage, materials from required excavation, availability and quality of offsite quarries, and turfs. A greater thickness of quarry-run stone may be an option to relatively expensive graded riprap. Some designers consider the quarry-run stone to have another advantage: its gravel- and sand-size components serve as a filter. The gravel and sand sizes should be less by volume than the voids among the larger stone. Not all quarry-run stone can be used as riprap; stone that is gap graded or has a large range in maximum to minimum size is unsuitable. Quarry-run stone for riprap should be limited to $D_{85}/D_{15} \leq 7$. Additional information is available in EM 1110-2-1601. A careful analysis should be made to demonstrate the economics of using the alternative.

(l) Upstream slope.

(a) Class I zone. One alternative to riprap is to use riprap-quality, quarry-run stone dumped in a designated zone within, but not at, the outer slope of the embankment. The dumped rock is spread and then processed by a rock rake operating in a direction perpendicular to the strike of the exterior slope. Rock raking will move the larger stones in the zone contingent to the exterior slope of the embankment. The quarry-run stone that remains in the dumped zone serves as a bedding. The size of the stone in the outer layer can be partially controlled by the blasting techniques, quarry handling of material, and by the tooth spacing on the rock rake. The outer zone of large stone should produce a thickness (normal to the slope) greater than the thickness of required layers of riprap protection. Another alternative is to use a well designed and properly controlled plant-mix, soil-cement layer placed with established and acceptable techniques. The Bureau of Reclamation pioneered in the development and use of soil-cement for upstream slope protection of dams (Holtz and Walker 1962, Bureau of Reclamation 1986, DeGroot 1971, Casias and Howard 1984, Adaska et al. 1990). Details concerning design and construction are available (Bureau of Reclamation 1986; Hansen 1986; Portland Cement Association 1986, 1988, 1991, 1992a, 1992b). The Tulsa District has used soil cement as upstream slope protection at Optima Dam, OK, Arcadia Dam, OK, and Truscott Brine Dam, TX (Denson, Husbands, and Loyd 1986).

(b) Class II zone. An alternative to riprap is quarry-run stone consisting of stones that may be of less than riprap quality. The quarry-run stone layer thickness is dependent on material quality and size, but should always be greater than the thickness of required layers of riprap protection.

(c) Class III zone. An alternative to riprap is layers of quarry-run materials or erosion-resistant materials in thicknesses greater than those designed for riprap. Slopes between 1 vertical on 8 horizontal and 1 vertical on 15 horizontal with a maintenance access to the slope may be protected by an erosion-resistant material with minimum thickness of 1 ft normal to the slope.

(2) Downstream slopes. The slope is usually protected by a layer of locally available, erosion-resistant material from required excavation or by turf. Designed intercepter ditches across the slope would be provided, where long unbroken surfaces exist or where the intersection of slopes steepen in a downslope direction. Sheet flow of surface runoff without the beginning of erosion gullies is seldom possible for distances greater than 200 ft. This is especially true in regions with semiarid climates. Because failure of an inadequately sized intercepter ditch or an improperly constructed ditch and dike can create serious erosion, it is important that intercepter ditches be carefully planned.

g. Erosion-resistant granular materials. Gravels and combination gravel and soft clay are resistant to erosion under many conditions. The resistance of gravels is dependent on the severity of erosion, steepness of the slope, size and shape of the gravels, and quantity and plasticity of fines. Compaction may be required to ensure satisfactory performance of some of these materials.

h. Erosion-resistant clays. The performance of a clay is hard to predict, but experience has shown some clays to be very resistant to erosive forces (Arulanandan and Perry 1983). Clay materials with a liquid limit above 40 percent and that plot above the “A” line would normally qualify as “erosion resistant.” When clay is used as an erosion-resistant material, an upper liquid limit should be specified. An upper liquid limit is selected to limit the low, long-term shear strength characteristics and changes in volume, expansion, and shrinkage, with changes in climate. Clays can also be used as underlayers for marginal slope protection at little additional cost. Erosion-resistant clays employed for slope protection should be compacted as specified for impervious fill.

i. Turfs. Turfs consisting of grasses suitable to local climate and tolerant to some inundation often provide sufficient resistance to erosion, including upstream Class III zones. A turf protection requires a soil layer that is capable of supporting vegetation. The topsoil and seeding operations should be performed during the growing season as the embankment construction proceeds. This procedure will minimize surface erosion on the unprotected embankment surface and will establish much of the surface turfing prior to the contractor’s departure from the site. To facilitate establishment of a turf and mowing the embankment, slopes should not be steeper than 1 vertical on 3 horizontal. In some climatic regions, turfs are not suitable alternatives for slope protection.

C-3. Stone Quality

Riprap protection requires good quality rock and bedding of sufficient size to meet the design requirements. Consideration should be given to materials available from required excavations as well as from the nearby quarry sources. Freeze-thaw, wet-dry, specific gravity, absorption, sodium sulphate soundness, and Los Angeles abrasion tests should be formed to determine the durability of the material under the anticipated field conditions (detailed test procedures are given in EM 1110-2-2302). Service records for proposed materials should be studied to evaluate how they have performed under field conditions.

C-4. Construction

Performance of riprap can only be realized by proper specifications and government inspection to ensure adherence to the specifications. The contract documents should identify sources and geologic formations that can produce acceptable material, provide controlled quarry blasting and production techniques, define gradation ranges and permissible percentages of undesirable materials, define permissible ratio of maximum to minimum particle dimensions, describe required particle quality, define layer thickness and allowable tolerances, describe required layer condition and restrictions to placement techniques, and define the quality control testing procedures and frequencies of performance. The control of blasting technique is important to prevent the development of closely spaced incipient fractures that open shortly after the weathering processes begin. Government inspectors should confirm that the slope protection materials meet the specifications and produce stable layers of interlocking particles.